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The reported e^\pm annihilation line from the Crab pulsar [See Fig. 1] has three remarkable properties. It is

1. very strong ($\sim 10^{40} e^\pm$ annihilations/sec.)
2. red shifted (by about 70 KeV relative to $mc^2 = 511$ KeV)
3. very narrow (width ~ 10 KeV)

A plausible model which gives all three properties has proven difficult to construct but there is one. We [T. Zhu and M.R.] found the following:

- a) Polar cap accelerator models could give an abundant outflowing pair flux of about 10^{38}s^{-1} , but not enough to explain property 1.
- b) The e^\pm annihilation did not occur near the star in such models so that the redshift, suggestive in its magnitude of a gravitational redshift from annihilation near the stellar surface, did not have an explanation. We, therefore, concentrated on e^\pm pair production from outer-magnetosphere accelerator models.
- c) Crossed beam geometry in such models did give abundant $\gamma + \gamma \rightarrow e^- + e^+$, capable (barely) of maintaining $\dot{N}_\pm \sim 10^{40} \text{s}^{-1}$ flowing down toward the stellar polar cap along the open field line bundle which joined the distant accelerator and the star (and a similar flux injected into the neutron star's wind).
- d) However, the density of that flux near the polar cap, $n_\pm \sim 10^{20} \text{cm}^{-3}$, was so great that the column of annihilating $e^+ + e^- \rightarrow \gamma + \gamma$ was not optically thin to the escaping γ -rays. This would cause unacceptably large γ -ray energy loss (more than the "observed" 70 KeV) and unacceptable line broadening.
- e) In such models with all of the \dot{N}_\pm constrained to flow to the star along the relatively small (10^{10}cm^2) open field line bundle near the stellar surface, pair annihilation occurs before the surface is reached. If this annihilation is before passage through a shock the large inflow speed gives unacceptable annihilation line energy shifts which vary greatly through the observed pulse (and thus would give an apparent huge line broadening). If the annihilation takes place after passage through a shock standing above the surface, the post-shocked e^\pm plasma is much too hot to give property 3.

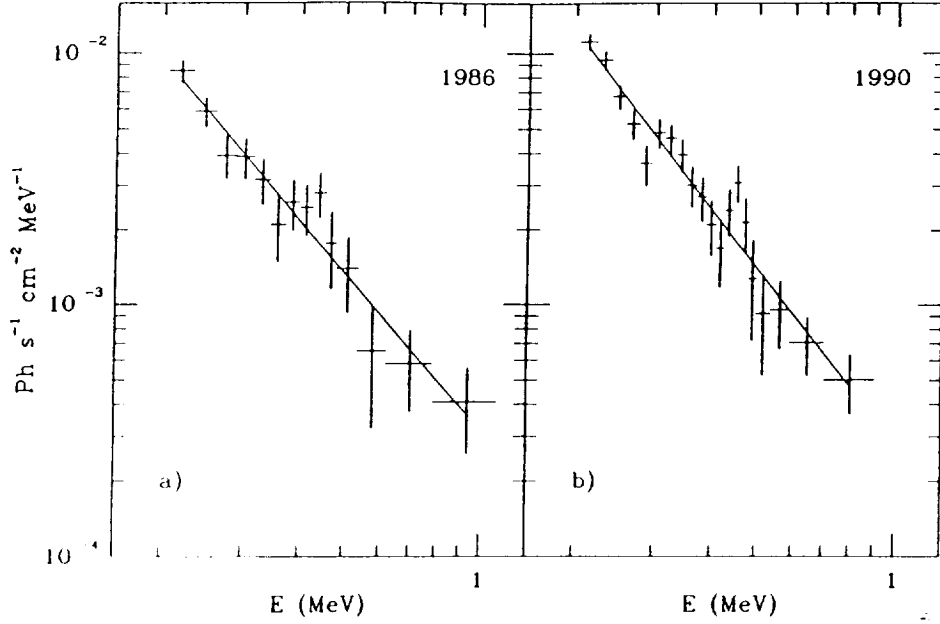


Fig. 1. The net spectra of the Crab photons after subtraction of the off-pulse signal, for the two FIGARO II flights of (a) 1986 July 11 and (b) 1990 July 9. From E. Massaro et al., *Ap.J.*, **376**, L11 (1991).

For all of these reasons we have reconsidered the entire problem raised by properties 1–3. A new model has emerged which at this time is the only one which does not appear to be incompatible with these properties.

The total X-ray and γ -ray emission from the Crab pulsar is about 10^{-3} of that neutron star's spin-down power ($-I\Omega\dot{\Omega}$). The scaling laws for the power from an outer-magnetosphere accelerator as a function of the fraction of the open field line bundle spanned by the accelerator then gives that fraction as $f \sim 10^{-1}$. The current flow through the accelerator (\dot{N}_a) is then that same fraction f of the total Goldreich-Julian current flow. For the Crab pulsar this flow is

$$\dot{N}_a \sim f\pi BR^3\Omega^2 e^{-1} c^{-2} f \cdot 10^{34} \text{s}^{-1} \sim 10^{33} \text{s}^{-1}. \quad (1)$$

Within the accelerator this \dot{N}_a flow is accelerated by an electric field along \vec{B} of magnitude $|\vec{E}| \sim f^2 BR^3\Omega^3 c^{-3} \sim 10^7 \text{Vcm}^{-1}$. The radiation reaction limited energies of accelerator e^-/e^+ are then large enough to give curvature radiation with γ -ray energies up to several GeV. Thus coming out of the starward end of the accelerator is a flow of $\dot{N}_a \sim 10^{33} \text{s}^{-1}$ of e^- (or e^+) which initially curvature radiate GeV γ -rays. Because $\vec{E} \cdot \hat{\vec{B}} \sim 0$ along the open field line path between the end of the accelerator and the polar cap these e^- (e^+) lose

much of their initial energy. They approach the polar cap with a Lorentz γ given by

$$\frac{1}{\gamma^3} - \frac{1}{\gamma_a^3} \sim \frac{2\Omega e^2}{mc^3} \ln \frac{r_a}{r}, \quad (2)$$

where γ_a is γ when leaving the accelerator at a distance $r_a \sim c\Omega^{-1}$ away from the star and r is the distance of the $e^-(e^+)$ from the neutron star. The energy of the curvature radiated γ -rays when the star is approached is

$$E_\gamma \sim \frac{\gamma^3 c^{1/2} \Omega^{1/2} \hbar}{r^{1/2}} \sim 10^2 \text{ MeV}. \quad (3)$$

The number of such curvature radiated γ -rays in a distance $(rc/\Omega)^{1/2}$ for each inflowing $e^-(e^+)$ is

$$\frac{\dot{N}_\gamma}{\dot{N}_a} \sim \frac{\gamma e^2}{\hbar c} \sim 10^5. \quad (4)$$

As long as $r \lesssim 10^7 \text{ cm}$ all of these γ -rays will be converted to e^\pm pairs by the neutron star magnetic field as they pass within a few stellar radii of the strongly magnetized star. From Eqs. (1) and (4) this would give only

$$\dot{N}_\pm \sim 10^5 \dot{N}_a \sim 10^{38} \text{ s}^{-1}. \quad (5)$$

However, there can now be a second generation of e^\pm pairs which is produced from the synchrotron radiation which must accompany the \dot{N}_\pm production of Eq. (5). The γ -rays of Eqs. (3) and (4) are initially radiated with a $\overrightarrow{\text{velocity}}$ almost exactly parallel to the \vec{B} along which their source $e^-(e^+)$ moves. Because of \vec{B} field-line curvature the angle (θ) between the γ -ray momentum and the local \vec{B} increases as the γ -ray approaches the star. The γ -ray will be converted to an e^\pm pair as soon as

$$E_\gamma \sin \theta > 2mc^2, \quad (6)$$

if

$$B \gtrsim 10^{12} \text{ G}. \quad (7)$$

If Eq. (7) is not satisfied then Eq. (6) must be replaced by

$$E_\gamma \sin \theta \gtrsim 2mc^2 / B_{12}. \quad (8)$$

From Eq. (6) – (7) or Eq. (8) the energy of the synchrotron γ -rays from these e^\pm pairs is

$$\begin{aligned}\hbar\omega_s &\sim \left(\frac{E_\gamma}{mc^2}\right) \left(\frac{E_\gamma \sin \theta}{mc^2}\right) \left(\frac{\hbar e B}{mc}\right) \\ &\sim \left(\frac{E_\gamma}{mc^2}\right) (10 \text{ KeV}).\end{aligned}\tag{9}$$

From Eq. (3) we have $\hbar\omega_s \sim 1 \text{ MeV}$ and a total pair production rate

$$\begin{aligned}\dot{N}_\pm(\text{total}) &= \dot{N}_\pm(\text{Eq.5}) \cdot \frac{E_\gamma(\text{Eq.3})}{\hbar\omega_s(\text{Eq.9})} \\ &\simeq \dot{N}_\pm(\text{Eq.5}) \cdot \left(\frac{mc^2}{10 \text{ KeV}}\right) \\ &\sim 10^{40} \text{ s}^{-1}.\end{aligned}\tag{10}$$

These pairs are produced all around the star within several radii of it and we no longer have the problems associated with such an \dot{N}_\pm confined to the small open field line bundle above the polar cap. A more detailed quantitative investigation has been done for the above model and it appears that the magnetic field structure must be somewhat (but not much) more irregular than that from a pure central dipole.

We have found that a large fraction of the e^\pm pairs produced in this way will annihilate (and at small velocities) at a distance about 17 km. from the center of the star. This is a consequence of the heating of the polar cap by the \dot{N}_a inflow of e^- (e^+) down onto the polar cap. Each of these particles brings in about 6 ergs and heats the polar cap area they impact upon to $kT \sim 1 \text{ KeV}$. Thus there is an emission from the polar caps of about $6 \cdot 10^{33} \text{ erg s}^{-1}$ of X-rays with a typical energy $E_x \sim 3 \text{ KeV}$. This flux is too small to greatly perturb the e^\pm plasma flow except at the positions around the star where $\hbar\omega_B \sim eB(r)\hbar/mc \cong 3 \text{ KeV}$.

At these r the X-ray-electron cross-section is resonant [$\sigma \sim (2\pi^2 e^2/mc)\delta(\omega_B - \omega)$] and the radiation pressure on the e^\pm plasma is very large. So is the inverse Compton drag there so that e^- and e^+ will tend to accumulate at special places where the net force of the radiation pressure is perpendicular to the local \vec{B} and also resonantly large. We have found that most favored is an equatorial belt at

$$\left(\frac{R}{r}\right)^3 \sim \left(\frac{15 \text{ KeV}}{3 \text{ KeV}}\right) = 5\tag{11}$$

or

$$r \sim (1.7)R \sim 1.7 \times 10^6 \text{ cm},\tag{12}$$

where $\hbar\omega_B$ at $r = R$ is about 15 KeV.

This would give about the “observed” annihilation line redshift from the gravitational redshift at this distance r from a $1.4M_\odot$ neutron star.

The line width remains a critical issue, but appears much more tractable than was the case in the previously considered models. In those cases $\Delta E \sim (\Delta v/c)mc^2$ and it was difficult to see what process could bring to rest the initially rapid flowing ($v \sim 10^{10} \text{ cm s}^{-1}$) e^\pm plasma to the needed precision. In the new model the resonant inverse compton drag from polar cap X-rays seems adequate. The main cause of ΔE would then be the variation in GM/rc^2 at resonance because $|\vec{B}|$ depends upon angle as well as r and because of the spread in polar cap X-ray energies. In either case $\Delta E \sim (\Delta r/r) \cdot 70 \text{ KeV}$ so that a considerable spread in dipolar B ($\Delta B/B \sim 3/7$) in the “resonance layer” is tolerable. So far we have examined only the variation in GM/rc^2 at fixed $|B|$ because of angular variation in the resonance position $r(\theta)$ and this does not give an unacceptable width.

Understanding the e^\pm environment around a γ -ray pulsar neutron star is a necessary preliminary for describing the soft X-rays which pass from the stellar surface through an outer-magnetosphere accelerator. It is especially important in deciding how that radiation is divided between direct polar cap emission ($kT \sim 1 \text{ KeV}$) and general surface emission ($kT \sim 10^{-1} \text{ KeV}$). The outer-magnetosphere accelerator for Vela, PSRs 1706 and 1055, and Geminga are proposed to be “bootstrapped” and limited by $X + \text{curvature } \gamma \rightarrow e^+ + e^-$. The curvature γ -rays need be only energetic enough for $E_x E_\gamma \gtrsim 2m^2 c^4$ and whether $E_x \sim \text{few } 10^{-1} \text{ KeV}$ or $\sim \text{few KeV}$ can be critical. The observed high energy γ -rays from the above pulsars should be direct curvature γ -rays from e^-/e^+ in the accelerator. Our next step will be to use observed X-ray emission to predict both the EGRET range γ -ray emission and the strength of possible e^\pm red-shifted annihilation lines in the γ -ray pulsars.